

VISIT...

LANZAROTE
Caliente.COM

ELECTRIC POWER DISTRIBUTION EQUIPMENT AND SYSTEMS

ELECTRIC POWER DISTRIBUTION EQUIPMENT AND SYSTEMS

T. A. Short

EPRI Solutions, Inc.
Schenectady, NY



Taylor & Francis

Taylor & Francis Group
Boca Raton London New York

A CRC title, part of the Taylor & Francis imprint, a member of the
Taylor & Francis Group, the academic division of T&F Informa plc.

The material was previously published in *Electric Power Distribution Handbook* © CRC Press LLC 2004.

Published in 2006 by
CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

© 2006 by Taylor & Francis Group, LLC
CRC Press is an imprint of Taylor & Francis Group

No claim to original U.S. Government works
Printed in the United States of America on acid-free paper
10 9 8 7 6 5 4 3 2 1

International Standard Book Number-10: 0-8493-9576-3 (Hardcover)
International Standard Book Number-13: 978-0-8493-9576-5 (Hardcover)
Library of Congress Card Number 2005052135

This book contains information obtained from authentic and highly regarded sources. Reprinted material is quoted with permission, and sources are indicated. A wide variety of references are listed. Reasonable efforts have been made to publish reliable data and information, but the author and the publisher cannot assume responsibility for the validity of all materials or for the consequences of their use.

No part of this book may be reprinted, reproduced, transmitted, or utilized in any form by any electronic, mechanical, or other means, now known or hereafter invented, including photocopying, microfilming, and recording, or in any information storage or retrieval system, without written permission from the publishers.

For permission to photocopy or use material electronically from this work, please access www.copyright.com (<http://www.copyright.com/>) or contact the Copyright Clearance Center, Inc. (CCC) 222 Rosewood Drive, Danvers, MA 01923, 978-750-8400. CCC is a not-for-profit organization that provides licenses and registration for a variety of users. For organizations that have been granted a photocopy license by the CCC, a separate system of payment has been arranged.

Trademark Notice: Product or corporate names may be trademarks or registered trademarks, and are used only for identification and explanation without intent to infringe.

Library of Congress Cataloging-in-Publication Data

Short, T.A. (Tom A.), 1966-
Electric power distribution equipment and systems / Thomas Allen Short.
p. cm.
Includes bibliographical references and index.
ISBN 0-8493-9576-3 (alk. paper)
1. Electric power distribution--Equipment and supplies. I. Title.

TK3091.S466 2005
621.319--dc22

2005052135

informa
Taylor & Francis Group
is the Academic Division of Informa plc.

Visit the Taylor & Francis Web site at
<http://www.taylorandfrancis.com>
and the CRC Press Web site at
<http://www.crcpress.com>

Dedication

To the future. To Jared. To Logan.

Preface

In industrialized countries, distribution systems deliver electricity literally everywhere, taking power generated at many locations and delivering it to end users. Generation, transmission, and distribution—of the big three components of the electricity infrastructure, the distribution system gets the least attention. Yet, it is often the most critical component in terms of its effect on reliability and quality of service, cost of electricity, and aesthetic (mainly visual) impacts on society.

Like much of the electric utility industry, several political, economic, and technical changes are pressuring the way distribution systems are built and operated. Deregulation has increased pressures on electric power utilities to cut costs and has focused emphasis on reliability and quality of electric service. The great fear of deregulation is that service will suffer because of cost cutting. Regulators and utility consumers are paying considerable attention to reliability and quality. Customers are pressing for lower costs and better reliability and power quality. The performance of the distribution system determines greater than 90% of the reliability of service to customers (the high-voltage transmission and generation system determines the rest). If performance is increased, it will have to be done on the distribution system. Utilities are looking for the most cost-effective and efficient management of their distribution assets.

This book is a spinoff from the *Electric Power Distribution Handbook* (2004) that includes the portions of that handbook that target equipment and applications of equipment. It includes overhead designs, underground issues and applications, and voltage regulation and capacitor applications. Managing these assets is key to controlling costs, regulating voltage, controlling maintenance, and managing failures. Proper specification, application, and maintenance will improve equipment reliability, which will help reduce costs, improve safety, and improve customer reliability.

I hope you find useful information in this book. If it's not in here, hopefully, one of the many bibliographic references will lead you to what you're looking for. Please feel free to e-mail me feedback on this book including errors, comments, opinions, or new sources of information—I'd like to hear from you. Also, if you need my help with any interesting consulting or research opportunities, I'd love to hear from you.

Tom Short
EPRI Solutions, Inc.
Schenectady, NY
t.short@ieee.org

Acknowledgments

First and foremost, I'd like to thank my wife Kristin—thank you for your strength, thank you for your help, thank you for your patience, and thank you for your love. My play buddies, Logan and Jared, energized me and made me laugh. My family was a source of inspiration. I'd like to thank my parents, Bob and Sandy, for their influence and education over the years.

EPRI Solutions, Inc. (formerly EPRI PEAC) provided a great deal of support on this project. I'd like to recognize the reviews, ideas, and support of Phil Barker and Dave Crudele here in Schenectady, New York, and also Arshad Mansoor, Mike Howard, Charles Perry, Arindam Maitra, and the rest of the energetic crew in Knoxville, Tennessee.

Many other people reviewed portions of the draft and provided input and suggestions including Dave Smith (Power Technologies, Inc.), Dan Ward (Dominion Virginia Power), Jim Stewart (Consultant, Scotia, NY), Conrad St. Pierre (Electric Power Consultants), Karl Fender (Cooper Power Systems), John Leach (Hi-Tech Fuses, Inc.), and Rusty Bascom (Power Delivery Consultants, LLC).

Thanks to Power Technologies, Inc. for opportunities and mentoring during my early career with the help of several talented, helpful engineers, including Jim Burke, Phil Barker, Dave Smith, Jim Stewart, and John Anderson. Over the years, several clients have also educated me in many ways; two that stand out include Ron Ammon (Keyspan, retired) and Clay Burns (National Grid).

EPRI has been supportive of this project, including a review by Luther Dow. EPRI has also sponsored a number of interesting distribution research projects that I've been fortunate enough to be involved with, and EPRI has allowed me to share some of those efforts here.

As a side-note, I'd like to recognize the efforts of linemen in the electric power industry. These folks do the real work of building the lines and keeping the power on. As a tribute to them, a trailer at the end of each chapter reveals a bit of the lineman's character and point of view.

About the Author

Mr. Short has spent most of his career working on projects helping utilities improve their reliability and power quality. He performed lightning protection, reliability, and power quality studies for many utility distribution systems while at Power Technologies, Inc. from 1990 through 2000. He has done extensive digital simulations of T&D systems using various software tools including EMTP to model lightning surges on overhead lines and underground cables, distributed generators, ferroresonance, faults and voltage sags, and capacitor switching. Since joining EPRI PEAC in 2000 (now EPRI Solutions, Inc.), Mr. Short has led a variety of distribution research projects for EPRI, including a capacitor reliability initiative, a power quality handbook for distribution companies, a distributed generation workbook, and a series of projects directed at improving distribution reliability and power quality.

As chair of the IEEE Working Group on the Lightning Performance of Distribution Lines, he led the development of IEEE Std. 1410-1997, *Improving the Lightning Performance of Electric Power Overhead Distribution Lines*. He was awarded the 2002 Technical Committee Distinguished Service Award by the IEEE Power Engineering Society for this effort.

Mr. Short has also performed a variety of other studies including railroad impacts on a utility (flicker, unbalance and harmonics), load flow analysis, capacitor application, loss evaluation, and conductor burndown. Mr. Short has taught courses on reliability, power quality, lightning protection, over-current protection, harmonics, voltage regulation, capacitor application, and distribution planning.

Mr. Short developed the Rpad engineering analysis interface (www.Rpad.org) that EPRI Solutions, Inc. is using to offer engineering, information, mapping, and database solutions to electric utilities. Rpad is an interactive, web-based analysis program. Rpad pages are interactive workbook-type sheets based on R, an open-source implementation of the S language (used to make many of the graphs in this book). Rpad is an analysis package, a web-page designer, and a gui designer all wrapped in one. Rpad makes it easy to develop powerful data-analysis applications that can be easily shared on a company intranet.

Mr. Short graduated with a master's degree in electrical engineering from Montana State University in 1990 after receiving a bachelor's degree in 1988.

Contents

1	Fundamentals of Distribution Systems	1
1.1	Primary Distribution Configurations	4
1.2	Urban Networks.....	9
1.3	Primary Voltage Levels	12
1.4	Distribution Substations	17
1.5	Subtransmission Systems	20
1.6	Differences between European and North American Systems	22
1.7	Loads	26
1.8	The Past and the Future	28
	References.....	30
2	Overhead Lines	33
2.1	Typical Constructions.....	33
2.2	Conductor Data.....	38
2.3	Line Impedances	43
2.4	Simplified Line Impedance Calculations.....	51
2.5	Line Impedance Tables.....	57
2.6	Conductor Sizing	57
2.7	Ampacities.....	61
2.7.1	Neutral Conductor Sizing	71
2.8	Secondaries	73
2.9	Fault Withstand Capability	74
2.9.1	Conductor Annealing.....	75
2.9.2	Burndowns.....	77
2.10	Other Overhead Issues.....	83
2.10.1	Connectors and Splices.....	83
2.10.2	Radio Frequency Interference.....	86
	References.....	88
3	Underground Distribution.....	91
3.1	Applications.....	91
3.1.1	Underground Residential Distribution (URD)	92
3.1.2	Main Feeders	94
3.1.3	Urban Systems.....	94
3.1.4	Overhead vs. Underground	95
3.2	Cables.....	98
3.2.1	Cable Insulation	99
3.2.2	Conductors.....	104

3.2.3	Neutral or Shield	104
3.2.4	Semiconducting Shields.....	106
3.2.5	Jacket	107
3.3	Installations and Configurations.....	108
3.4	Impedances	111
3.4.1	Resistance	111
3.4.2	Impedance Formulas.....	114
3.4.3	Impedance Tables.....	121
3.4.4	Capacitance	121
3.5	Ampacity	123
3.6	Fault Withstand Capability	136
3.7	Cable Reliability	139
3.7.1	Water Trees.....	139
3.7.2	Other Failure Modes	142
3.7.3	Failure Statistics	144
3.8	Cable Testing	147
3.9	Fault Location.....	148
	References.....	153
4	Transformers	159
4.1	Basics	159
4.2	Distribution Transformers	164
4.3	Single-Phase Transformers	166
4.4	Three-Phase Transformers	174
4.4.1	Grounded Wye – Grounded Wye	179
4.4.2	Delta – Grounded Wye	183
4.4.3	Floating Wye – Delta.....	183
4.4.4	Other Common Connections	185
4.4.4.1	Delta – Delta	185
4.4.4.2	Open Wye – Open Delta.....	186
4.4.4.3	Other Suitable Connections	189
4.4.5	Neutral Stability with a Floating Wye	189
4.4.6	Sequence Connections of Three-Phase Transformers	191
4.5	Loadings	191
4.6	Losses	197
4.7	Network Transformers.....	201
4.8	Substation Transformers	202
4.9	Special Transformers	206
4.9.1	Autotransformers.....	206
4.9.2	Grounding Transformers	207
4.10	Special Problems	210
4.10.1	Paralleling	210
4.10.2	Ferroresonance	211
4.10.3	Switching Floating Wye – Delta Banks.....	220
4.10.4	Backfeeds.....	223

4.10.5	Inrush.....	226
	References.....	229

5	Voltage Regulation.....	233
5.1	Voltage Standards	233
5.2	Voltage Drop	236
5.3	Regulation Techniques	238
5.3.1	Voltage Drop Allocation and Primary Voltage Limits.....	238
5.3.2	Load Flow Models	240
5.3.3	Voltage Problems	242
5.3.4	Voltage Reduction.....	243
5.4	Regulators	245
5.4.1	Line-Drop Compensation	249
5.4.1.1	Load-Center Compensation	250
5.4.1.2	Voltage-Spread Compensation	253
5.4.1.3	Effects of Regulator Connections	257
5.4.2	Voltage Override	258
5.4.3	Regulator Placement	258
5.4.4	Other Regulator Issues.....	259
5.5	Station Regulation.....	260
5.5.1	Parallel Operation.....	261
5.5.2	Bus Regulation Settings.....	262
5.6	Line Loss and Voltage Drop Relationships	262
	References.....	266

6	Capacitor Application	269
6.1	Capacitor Ratings.....	273
6.2	Released Capacity	276
6.3	Voltage Support.....	277
6.4	Reducing Line Losses.....	280
6.4.1	Energy Losses	283
6.5	Switched Banks	284
6.6	Local Controls.....	286
6.7	Automated Controls	288
6.8	Reliability	290
6.9	Failure Modes and Case Ruptures.....	291
6.10	Fusing and Protection	295
6.11	Grounding	307
	References.....	309

Credits

Tables 4.3 to 4.7 and 4.13 are reprinted with permission from IEEE Std. C57.12.00-2000. *IEEE Standard General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers*. Copyright 2000 by IEEE.

Figure 4.17 is reprinted with permission from ANSI/IEEE Std. C57.105-1978. *IEEE Guide for Application of Transformer Connections in Three-Phase Distribution Systems*. Copyright 1978 by IEEE.

Tables 6.2, 6.4, and 6.5 are reprinted with permission from IEEE Std. 18-2002. *IEEE Standard for Shunt Power Capacitors*. Copyright 2002 by IEEE.

Table 6.3 is reprinted with permission from ANSI/IEEE Std. 18-1992. *IEEE Standard for Shunt Power Capacitors*. Copyright 1993 by IEEE.